Observation and Analysis of Vertical Electric Fields in the Earth

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Summary

We have been measuring and recording natural horizontal electric and magnetic fields at two sites on the San Andreas Fault near Parkfield and Hollister, California for the past ten years. The objective of the monitoring program was to determine objectively whether anomalies in either of these fields, or in the impedance of the ground, were observed in association with earthquakes on the San Andreas Fault. As part of a more general plan to study the behavior of the natural ULF and ELF fields, we installed a pair of electrodes in a vertical borehole used to deploy a deep three-component seismometer. The vertical dipole was connected to a spare channel of the seismic acquisition system and recorded along with the regular horizontal E and H data in the period from 01July 2004 to 01November 2005. The vertical field data displayed a long-term drift over the first few months of operation and a strong diurnal component as well as small variations (micropulsations) typically seen in the horizontal electric fields. We also discovered four striking variations of a few days duration in the recording. These anomalous fields stand out dramatically above the normal micropulsation signals. These signals are significant because: a) There is no counterpart variation in the horizontal electric fields at a station only 1.6 km away; b) No signals like this have been seen on the horizontal electrodes at any time; c) There were no rainfall events immediately prior to any of these anomalous variations; d) No particular pumping or hydrofracture experiments were conducted on the nearby SAFOD deep drilling site at these times. We propose to connect two more vertical dipoles to the network and to acquire two years of observations of this newly discovered phenomena. The horizontal field arrays will be maintained to provide the complimentary data to the three vertical dipoles. In addition we have access to the data from five volumetric strainmeters, at least two tiltmeters, and a long period seismograph all in the vicinity of the vertical electric dipole holes. The objective of the proposal is to study the relationship between vertical electric fields and the other geophysical data to try and determine the cause of the vertical field anomalies. Additionally, through a study of the ionospheric electron content provided by the GPS array, we will investigate whether there is a relationship between the vertical electric fields and ionospheric properties.

Existing Sites and Instrumentation

The borehole, which is equipped a vertical electric dipole, is labeled as CCRB in Figure 21.1. The site is between the SAFOD borehole and the PKD electromagnetic observatory. Apart from the orientation of the dipole, the instrumentation and data logging are identical to that described in the Parkfield-Hollister Monitoring Array chapter of this issue.

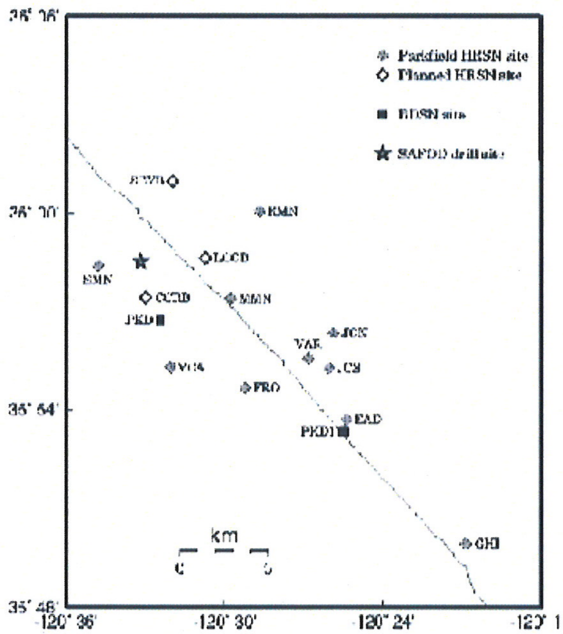

Figure 21.1: Location of borehole network, also showing SAFOD borehole, and PKD ULF observatory, and various other sites with geophysical data acquisition equipment.

Vertical Electric Dipole Data

The long term timeseries of the vertical electric dipole data is displayed in Figure 21.2. For brevity we include zoom-plots of only the first anomaly labeled as A.

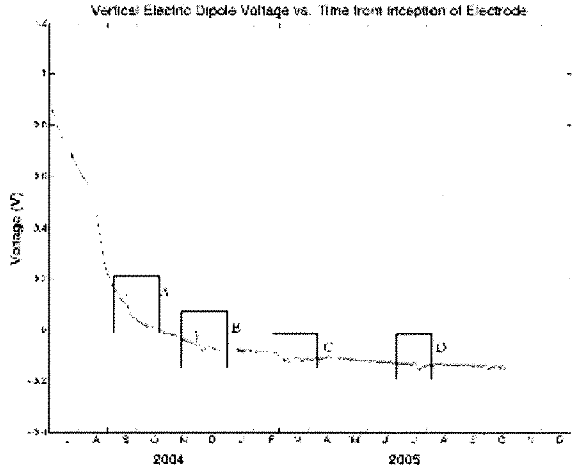

Figure 21.2: The vertical electric field data spanning 16 months of acquisition, mean subtracted. Boxes A-D indicate significant anomalies in the data stream.

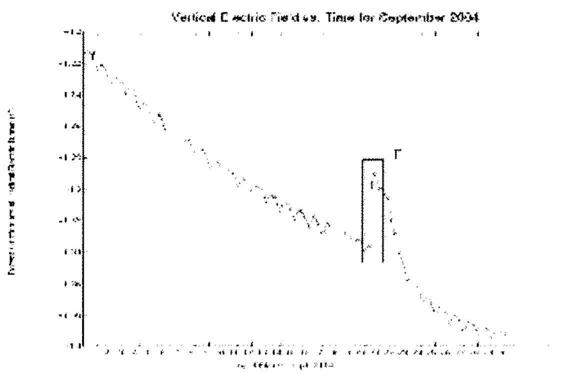

Figure 21.3: A closer look at the first spike in September 2004, shown above in box A.

The sharp offset depicted in Figure 21.3 looks suspiciously like an instrument step at this scale, but a closer inspection (Figure 21.4) shows that the onset of the step is in fact smooth.

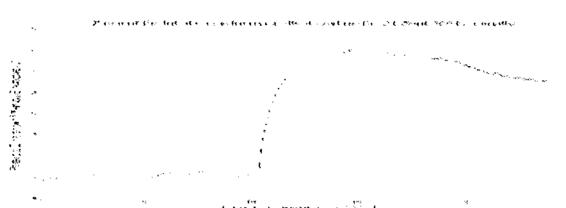

Figure 21.4: Shows the onset of the 21 September 2004 anomaly. The rise-time appears to be on the order of several hours. Once corrected for instrument response the rise is about is about 10mV.

The sharp corner also shows itself to be smooth in time when the 40Hz data are examined over short time intervals.

Preliminary Analysis

We have found only two previous studies on measurements of vertical electric fields in the ground, at depths below the near-surface soil/unconsolidated materials. *Colangelo et. al.* (2005) report on data from a shallow pair of electrodes. The data is noisy as would be expected when at least one electrode is in a near surface layer where surface moisture and chemistry is highly variable, temperature effects are strong and local streaming potentials are prevalent. *Corwin* (1990) presents a good review of the factors that can cause time variations of tens of millivolts in shallow electrode systems. None of these factors seem relevant for electrodes buried below the water table at depths of 100 or 200 meters. *Antonopoulous et. al.* (1993) report vertical electric fields from two adjacent drill holes on an island in Greece. The electrodes at depth were at 200m, but the upper electrodes were at the surface and, as noted above, subject to variations due to the near surface layer. Nonetheless, both vertical electrodes showed high coherence to a horizontal dipole many miles away, basically showing the same relationship between horizontal and vertical fields that we discussed above for our data. In addition, they claim that anomalous vertical fields were seen, related to distant horizontal fields of similar waveform, that were not related in the same manner as the magnetotelluric fields. These anomalous fields were of 15-20 minute duration and were claimed to be related to distant earthquakes. No anomalies of the type we report were described in their paper.

The anomalous variations seen in Figure 21.2 are well above the background micropulsation variations and are readily identified by eye. It is entirely possible that there are smaller variations down to the level of the micropulsations that are not coherent with the horizontal fields and are indicative of this new vertical field phenomenon. We have developed analysis techniques for the horizontal array studies that can identify such phenomena. In general, *Egbert* (1989) and *Booker and Egbert* (1989), have shown that all the components of electric and magnetic field measured on the surface of the ground that are caused by widespread sources in the ionosphere/magnetosphere are related by simple tensor forms. For example orthogonal electric fields at site A are related to orthogonal electric fields at site B by a simple 2x2 tensor. Over time this transfer function can be determined accurately. It is a function only of the conductivity distribution in the ground and has been found to be generally time invariant. Following similar reasoning the relationship between the vertical field and the orthogonal horizontal fields is described simply by a spectral transfer function of the form:

$$E_z = T_{xz}E_x + T_{yz}E_y \tag{21.1}$$

where E_i represents the ith component of electric field, and T is a simple 1x2 tensor. The multiple coherence between Ez and the horizontal components provides a measure of the noise in the measurement of the E s. An estimation of this transfer function can be made during a time of good data quality and then used to predict the fields at one site from those at another. The difference between the measured and predicted fields, which we labeled as a residual, becomes a measure of the fields at one site that are not components of the micropulsation source. Of course there is always a residual, which is the noise level of the measurements. So anomalous fields can be assigned a quantitative signal to noise level. *Egbert* (2000, 1997, and 1986) generalized this idea so as to use all the field components measured in two arrays to predict the fields in any one component of either array. This was the basic approach used with the ULF array in an attempt to isolate anomalous electric or magnetic fields that might have been generated by some earthquake related process local to one of the sites. This concept can also be applied in the time domain to yield estimates of electric field as a function of time. In this project we propose to calculate the time domain residuals in the vertical fields using the horizontal components of E and H at site PKD for the reference site. In this way other anomalies of a much smaller scale than the large ones highlighted in Figure 21.2 can be quickly identified.

Theory

The cause of these vertical field variations is not known. By measuring something that no one seems to have measured before, we may have discovered an interesting process within the earth or a heretofore unexpected coupling between the earth and the ionosphere. At the very low frequencies considered here, conventional wisdom suggests that there are no vertical electric fields at or within a conductor below free space that has an electric charge or field distribution. Within an inhomogeneous half space, there may, of course, be vertical components of the electromagnetically induced telluric currents which, in fact, we do observe.

The simplest explanation is that the observed vertical fields arise from the charge separation that occurs from the streaming potential phenomenon accompanying the development of a vertical pressure gradient. There are two possible sources for such a vertical pressure gradient: a) atmospheric loading leading to the diffusion of a pressure front into the earth or b) a reduction of pressure within the earth due to a dilatational strain. We briefly analyzed the first of these possibilities by plotting the atmospheric pressure variations at station VCA (Figure 21.1), 4.5 km from CCRB in Figure 21.5. In general the vertical field does not track the pressure variations.

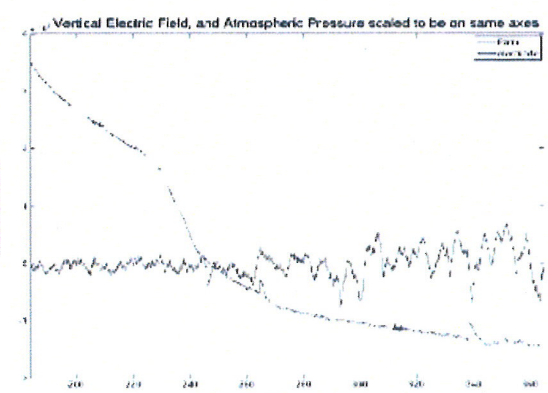

Figure 21.5: Variations of atmospheric pressure plotted together with variations in electric field. No clear correlation between the two signals stands out. The y-axis represents scaled instrument counts, and is only a qualitative measure.

Pride (2004) has recently shown that fluid sources or sinks within the ground will only produce vertical electric fields near the surface, not horizontal fields. Local fluid flow transients near the well bore could also cause streaming potentials, but the lack of any correlation with local rainfall and the long time scale of the variations argues against this explanation. *Pride* (2004) also argues that large-scale strain changes after an earthquake should produce long term variations in the streaming potentials with accompanying measurable vertical fields. A cursory examination of the vertical field data after the Parkfield (M= 6.0) earthquake on 28 September 2004 (day 272 UT), shows no such trends. A dilatancy strain could certainly produce vertical pressure gradients with associated vertical streaming potentials. We would expect to see some evidence of this in local measurements of strain. We examined the uncorrected strain data from VCA and found, as expected, that the strain tracks the atmospheric pressure changes and the local tidal strain. No anomalous strain associated with the electric field anomalies could be seen in the raw data. We propose to examine the corrected strain data from these sites at the times of the vertical field anomalies. After correction for tidal and atmospheric loading, the noise level for these strainmeters is approximately 0.1 nanostrain [*Malcolm Johnston*, USGS, personal communication, 2006]. These data and the vertical field and ULF array data are directly available from the NCEDC. Another intriguing possibility is that there is some electrical coupling among very low frequency gravity waves, ionospheric properties, local strain and the vertical electric field. *Calais and Minster* (1995) report on the detection of ionospheric perturbations caused by atmospheric-ionospheric-acoustic-gravity waves that were generated by the ground displacement of the 1994 Northridge earthquake. The ionospheric anomalies were found from an analysis of the phase delays on the two GPS frequencies, which are, in turn, proportional to the electron content of the ionosphere. More subtle transient ground displacements, on the order of 3-5 days, might consequently generate GPS phase delays corresponding to the vertical electric field. As mentioned above it is unlikely that ionospheric fluctuations of such a timescale, essentially electrostatic, could themselves cause the observed fields within the conductive earth.

Future Analysis

We have submitted an NSF proposal to monitor the vertical electric fields at three sites (LCCB, SCYB, CCRB). We intend to calculate the time domain residuals in the vertical fields using the horizontal components of E and H at site PKD (Figure 21.1) for the reference site. In this way other anomalies of a much smaller scale than the large ones highlighted in Figure 21.4 can be quickly identified. Other geophysical measurements that are available to correlate with the anomalous vertical fields basically break into ground and ionospheric. On the ground we have access to the following measurements in the vicinity of the PKD site:

1) The broadband seismometer co-located with the ULF monitoring sensors at PKD. 2) Tiltmeters located at VAR and GHI on Figure 21.1.

3) Volumetric strainmeters located at FRO and VCA on Figure 21.1., and also at three other sites (DLT, JCN, RHL, not shown) within 40 km.

4) Long period magnetic field observations from Fresno Magnetic observatory

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Next: Surface Deformation and Fault **Up:** 2005-2006_Annual_Report **Previous:** Parkfield-Hollister Electromagnetic Monitoring Array

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